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EXPERIMENTATION OF FIBER-OPTIC TRANSMISSION OF LIGHT WITH ORBITAL ANGULAR MOMENTUM

SUNY College at Oneonta

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13. ABSTRACT *(Maximum 200 Words)*
The fiber-optic transmission of Laguerre-Gaussian photons carries the potential for removing the inconvenience of alignment and space required in free-space experimentation while introducing a severity of power loss caused by coupling inefficiency as the profile propagates through the fiber-optic components. This experimentation was planned to gain some insight into the behavior of the Laguerre-Gaussian profile when transmitted through fiber-optic channels in order to have the ability to set up a quantum system which is part free space and part fiber-optic since the LG-profiles have to be created in free space. The free space research on computer generated holograms for profile generation, liquid crystal retarders for modulation of the absolute phase, the Mach-Zehnder interferometer and the orbital angular momentum sorter as well as the Spatial Light Modulator for the work under the senior fellowship continued side-by-side during the summer, while waiting for the equipment because all of these are going to contribute to the overall quantum information (QI) research at the Air Force Research Laboratory at Rome, NY.

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Table of Contents

List of Figures

1. INTRODUCTION

Light with orbital angular momentum, called a Laguerre-Gaussian (LG) beam, has demonstrated properties that would enable it to play a key role in the field of quantum information processing. The ordinary laser source produces a Hermite-Gaussian (HG) beam of light and does not generate these LG light profiles which are of great interest to people working with quantum information systems such as quantum communication systems and quantum key distribution. One way to generate an LG beam is to pass the HG beam through a computer generated hologram that can be created with relative ease.

These computer generated holograms have been created in our lab using published algorithms and the MATLAB and ADOBE PHOTOSHOP software. LG beam profiles of arbitrary charge are now available and experiments using some of those beam profiles are running in the lab. The profiles are being characterized using simple free space optics experiments for help in designing experiments related to Quantum Information. However, the process of alignment in free space experiments being rather cumbersome, the next round of experimentation would naturally be on the transmission of LG profiles through fiber optic channels, as proposed for this grant, and then through polymer waveguides which offer more efficient transmission but involve a great deal of research effort in design and fabrication.

As written in the proposal, if the LG profiles transmitted well through optical fibers, it would be worthwhile to run fiber-optic experiments on their polarization and phase characteristics, especially on how to control those properties for quantum communication and key distribution (QKD) purposes. Another interesting aspect would be the setting up of a Mach-Zehnder interferometer using optical fibers and the LG profiles.

This grant has enabled the initiation of fiber-optic experimentation on the LG profiles and fiber-optic parallels of some of the free space experiments have been set up. Some initial data have been recorded on the intensity and polarization for both Hermite-Gaussian and Laguerre-Gaussian beams. However, as reported in the interim report, the fiber-optic experimentation was slowed down by the process of equipment acquisition and the work on the grant was redesigned to include the on-going free space research on the LG profiles. This report will reflect that also.

The fiber-optic transmission of Laguerre-Gaussian photons carries the potential for removing the inconvenience of alignment and space required in free-space experimentation while introducing a severity of power loss that needs to be overcome as the profile propagates through the fiber-optic components. This experimentation has been planned to gain some insight into the behavior of the Laguerre-Gaussian profile when transmitted through fiber-optic channels in order to have the ability to set up a quantum system which is part free space and part fiber-optic since the LG-profiles have to be created free space and, in case the polarization controller does not perform as expected, the fiber-optic modulation of the absolute phase is likely to be free space as well. However, the initial experimentation has been done using the Hermite Gaussian profile from a fiber-coupled diode laser.

As mentioned above, the lab continues to grow but has yet to reach its full potential and this has caused a delay in following the tasks as proposed for the summer fellowship. Consequently a multi-pronged approach has been maintained to help prepare for the variety of tools needed for quantum information processing as follows:

1. Fiber-Optic set up
2. Computer Generated Holograms
3. The OAM Sorter
4. Liquid Crystal Wave Plates
5. Spatial Light Modulator

These are all equally important and essential for a comprehensive research on QI processing and therefore being pursued simultaneously, as directed by the availability of equipment. The fiber-optic experimentation has just started to yield data which are presented in the following together with some information on the free-space experimentation.

2. THE EXPERIMENTATION:

1. **Fiber-Optic set ups:** The work involved a search for information on fiber-optic components equivalent to their free space counterparts, preparation of a list thereof and contacting vendors followed by purchase of equipment, set up and testing with Gaussian beams.

As proposed in the statement of work for this grant, the expected results of this research include some information on the following for the Laguerre-Gaussian profiles of various orders using optical fibers:

1. Power transmission and control thereof.
2. Polarization transmission and control thereof.
3. Phase transmission and control thereof.
4. An attempt at the Mach-Zehnder set-up.

However, it has been found more convenient to start the experiment using the Hermite-Gaussian profile because in that case the set up can be made fully fiber-optic. In case of the Laguerre-Gaussian profile, it has to be created in free space and therefore the circuits are hybrids of free-space and fiber-optic.

The Fiber-Optic Circuits

We have started with simple circuits to transmit a Hermite-Gaussian beam profile first and then LG profiles for measurement of power, free-space check of polarization and phase changes using ordinary linear analyzers, a voltage driven liquid crystal retarder, and a manual fiber polarization controller.

We are using some of the following equipment for the fiber-optic experiments; a few of which will be ordered on next year’s budget since the research is continuing. The fibers are single mode.

Item number	Description
FPC560	Fiber Polarization Controller
FC632-50-FC	Split Ratio Coupler 632nm, 50/50
F230FC-B FC	Collimation Pkg, 600-1050nm AR Coating
S1FC635	Fiber Coupled Laser Source 635nm,2.5mW
PM120	Handheld Power Meter System w/Si Sensor
PDA55	Detector, Amplified, Si, 10MHz, Switchable Gain
P1-630A-FC-10	Singlemode Fiber Patch Cabl 10m, 633/680nm, FC/PC
ADAFC2	FC to FC Square Mating Sleeve

The source we are using is a fiber-coupled 5mW diode laser fitted with a collimator enabling free space connectivity. We will however need a fiber-coupled collimator for the fiber-optic experimentation using both HG (fiber-optic) and LG (free space) profiles.

The power meter (Newport Power meter Model 2930C) plus detector (Newport Low-power detector Model 918) we are using currently, is a highly sensitive one, capable of sensing nano-watts. However, the adapter plate needed for fiber coupling has yet to arrive making the current readings faulty.
Fig 1 Power circuit
Fig 2 Polarization circuit
Fig 3 Phase circuit

2. **<u>Computer Generated Holograms</u>** (Fig 4)**:** Since the holograms are the only way to get the LG profiles with orbital angular momentum, work on these has continued through the summer. Having had a remarkable improvement on charge 2 using MATLAB and ADOBE image processing, charges 1 and 3 have been focused on in preparation for the free space OAM sorter which needs a mix of odd and even states as input.

3. **<u>The OAM Sorter</u>** (Fig 5)**:** The free space sorter has been set up, which involved a great deal of effort in the alignment process. A $LiNBO_3$ modulator has been ordered and is expected to enable an absolute phase change required for interference of the even and odd states. Using polymer plates, an effect favorable to the sorting process has been observed. Currently screens are being used to examine the images exiting the sorter and will eventually be replaced by detectors since the light gets highly attenuated after passing through several optical components. The importance of the sorter lies in its equivalence in phase control to the polarizing beam splitter in polarization control in QI experiments.

4. **<u>Liquid Crystal Wave Plates/Retarders (</u>**Appendix)**:** The LC wave plates purchased earlier are mostly used for controlling the relative phase of the polarization components. However, it is possible to use these for changes in the absolute phase also by aligning the linear polarization of the LG beam with one of the axes of birefringence. We are experimenting on that while waiting for the modulator to arrive.

5. **<u>Spatial Light Modulator</u>** (Fig 6)**:** The literature shows that these liquid crystal modulators are capable of creating perfect LG profiles. The lab has been equipped with two of these SLMs. The hardware and software have been installed on the computer. Calibration and testing will follow and the literature is being reviewed for related information. This work on the SLMs is expected to prepare us for the project proposed for the second year of the NRC senior fellowship.

3. SOME RESULTS OF THE EXPERIMENTATION

The results of the free space and fiber-optic experimentation have been encouraging. However the process is understandably plagued by the difficulties associated with equipment acquisition, testing, calibration etc.

<u>1. The results of the fiber optic experimentation (1, 2, 3) are as follows:</u>

a) The power reading was taken

(1) at the end of the fiber (3mW);

(2) at the end of each arm of the 50/50 splitter (1μW without refractive index matching gel on the connectors and 8 μW with the gel on); this is a very high loss and the work on the adapter for the detector continues in order to improve the output to at least 2mW;

(3) Consequently, the 10m patches purchased for the Mach-Zehnder set up and the polarization controller for one arm of the interferometer did not transmit any visible spot. It is anticipated that when the adapter plates come in, the transmission will improve and better data will be available.

b). The polarization was checked at the input and was found to be elliptical. However when checked at the two ends of the splitter, the polarization became linear and mutually orthogonal, as appropriate for a polarization controlled fiber, similar to the polarizing beam splitter.

c). The phase control could not be tested due to severe loss in the patches since the polarization controller had one of the patches wrapped around it and the lack of the 2 to 1 coupler. An attempt was made in a partially free space manner by replacing the coupler with a dichroic beam-splitter and bringing the split light together on it from the splitter itself. The overlap was obtained; however, the interference pattern couldn't be created owing to the lack of the modulator. We did not want to damage the splitter fiber by wrapping it around the polarization controller, although we could have, to check for phase modulation. It is hoped that the liquid crystal retarder will act as an absolute phase modulator to yield the interference pattern while we wait for the modulator to arrive.

<u>The results associated with 2, 3, 4, and 5 in the previous section</u> are self explanatory in the paragraphs presented there. There are no numerical data to be expected as of yet until the modulator and the sorter work as they should and we have a good interference between states and the sorter sorts the odd and even states from the interference pattern.

2. The computer generated hologram of charge 3 as prepared using MATLAB, and ADOBE PHOTOSHOP has been presented. Some literature was reviewed in order to locate information on simulating blazed holograms for possible improvement of the profiles.

3. A picture of the free space set up for the Orbital Angular Momentum sorter (4) has been presented. A plastic plate inserted in one of the arms of the Mach-Zehnder set up seems to create a phase change that causes the charge 2 image to show preference in one direction. However, the preference of charge 1 or 3 to follow the orthogonal path wasn't quite as obvious although somewhat observable. It must be mentioned that the sorter is not established to be so until an interference pattern is introduced into it and it separates the states along orthogonal paths.

4. The liquid crystal retarder showed response to the voltage application by varying the intensity of the light, turning a linear polarization into elliptic and circular polarization. However, it has turned out to be much more difficult to get it to modulate the absolute phase for help with the interference pattern of the Mach-Zehnder interferometer due to the difficulty of aligning the extraordinary axis of the crystal with the incoming polarization. Several different polarization set ups are being tried.

5. Due to time constraints, the work on the Spatial Light Modulator has been limited to sorting out the test to generate a profile and reviewing the literature on its calibration.

4. FUTURE WORK

All of the research activities mentioned above are going to continue through the year 2005-2006 under a Senior Fellowship of the National Academy of Science, although the proposal for the fellowship focuses on a communication system using the Spatial Light Modulator for generating beam profiles and interference patterns for encoding and decoding messages.

5. BUSINESS/FINANCIAL ASPECTS OF THE AGREEMENT

Agreement No: FA8750-05-1-0181
Budget (Total amount of the agreement/Government share): $22,101.00

The grant was expended on a VFRP summer research at the rate of $1450/week for 12 weeks as detailed in the interim and final invoices (form 270).

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4. Allen, L., Barnett, Stephen M., and Padgett, Miles J.: Optical Angular Momentum, IOP Publishing Ltd. and individual contributors 2003.

7. APPENDIX A - FIGURES

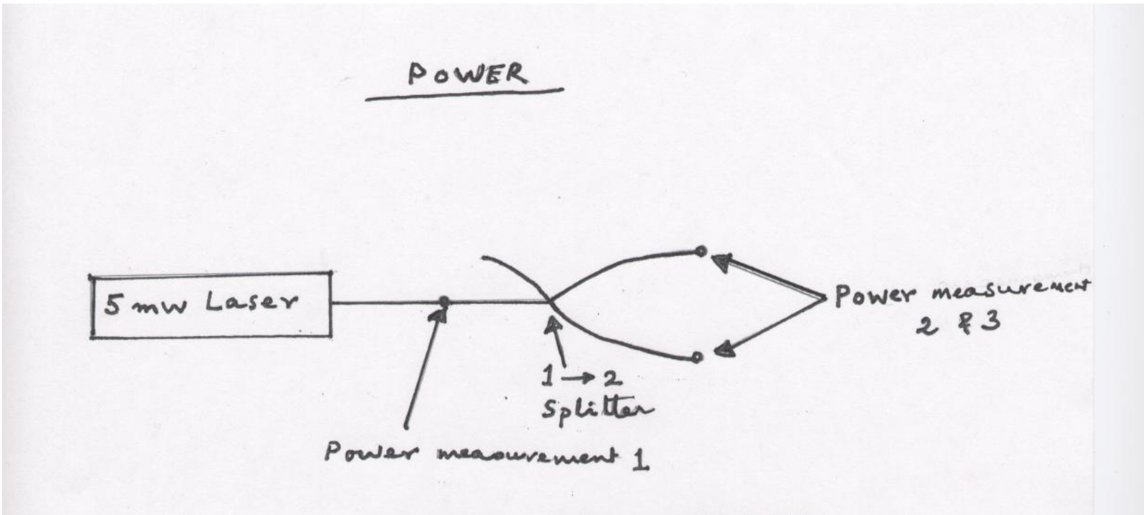


Figure 1 Power Measurements

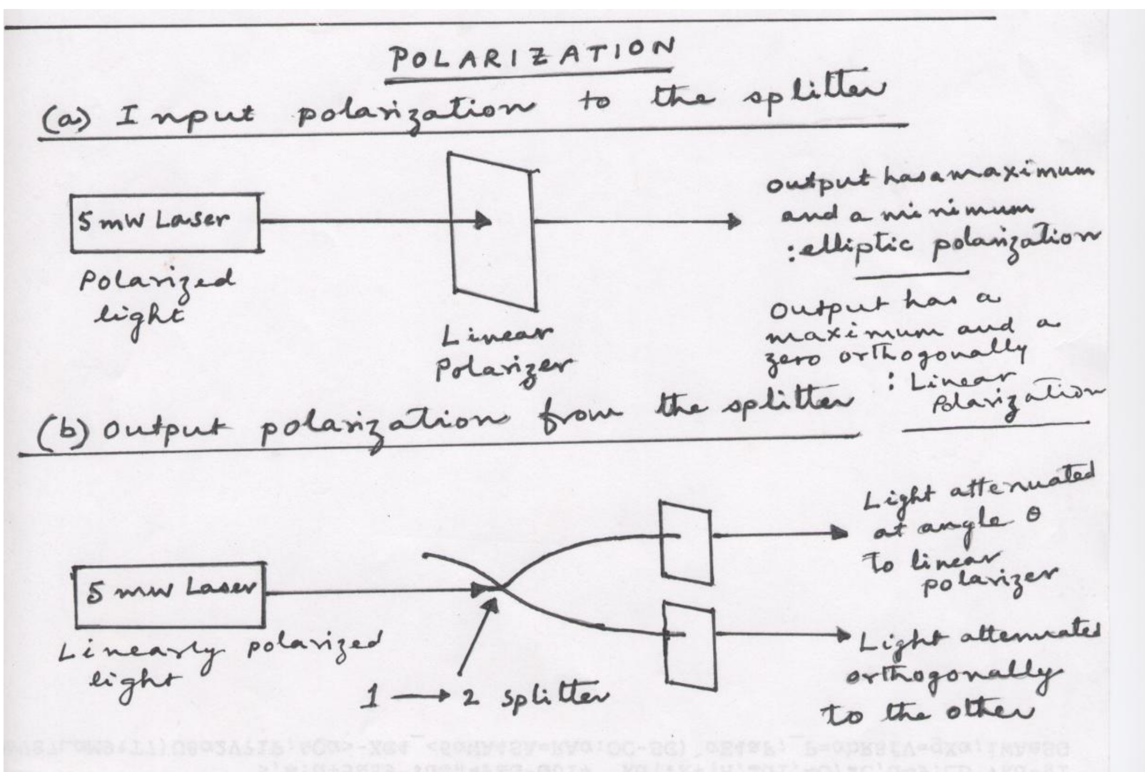


Figure 2 Polarization Test

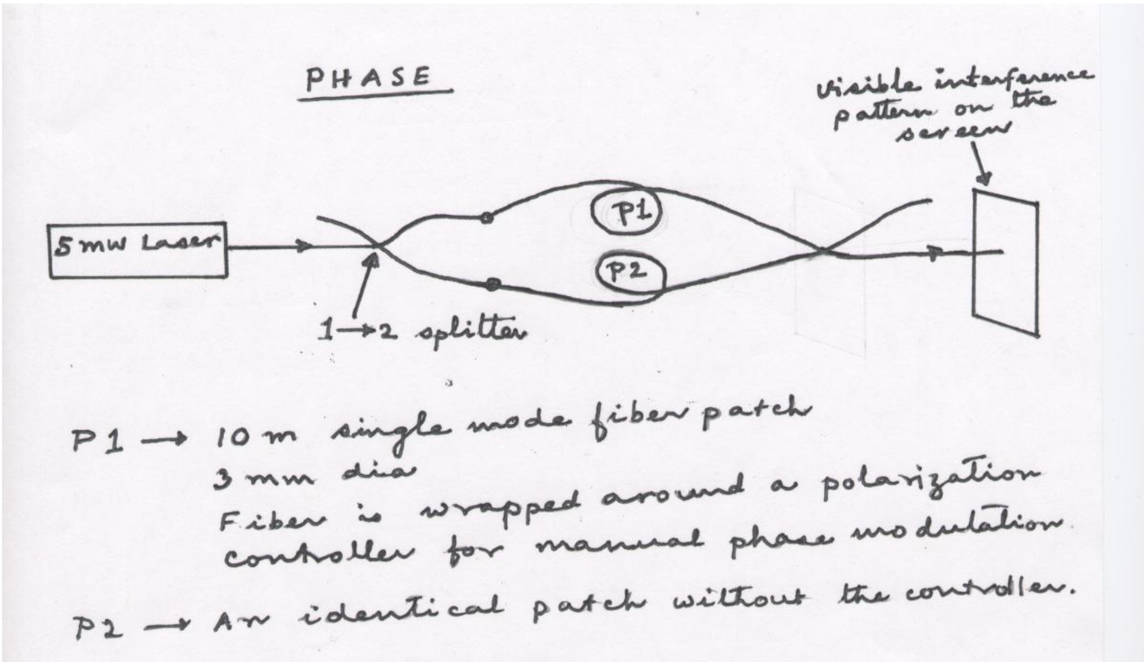


Figure 3 Phase Test

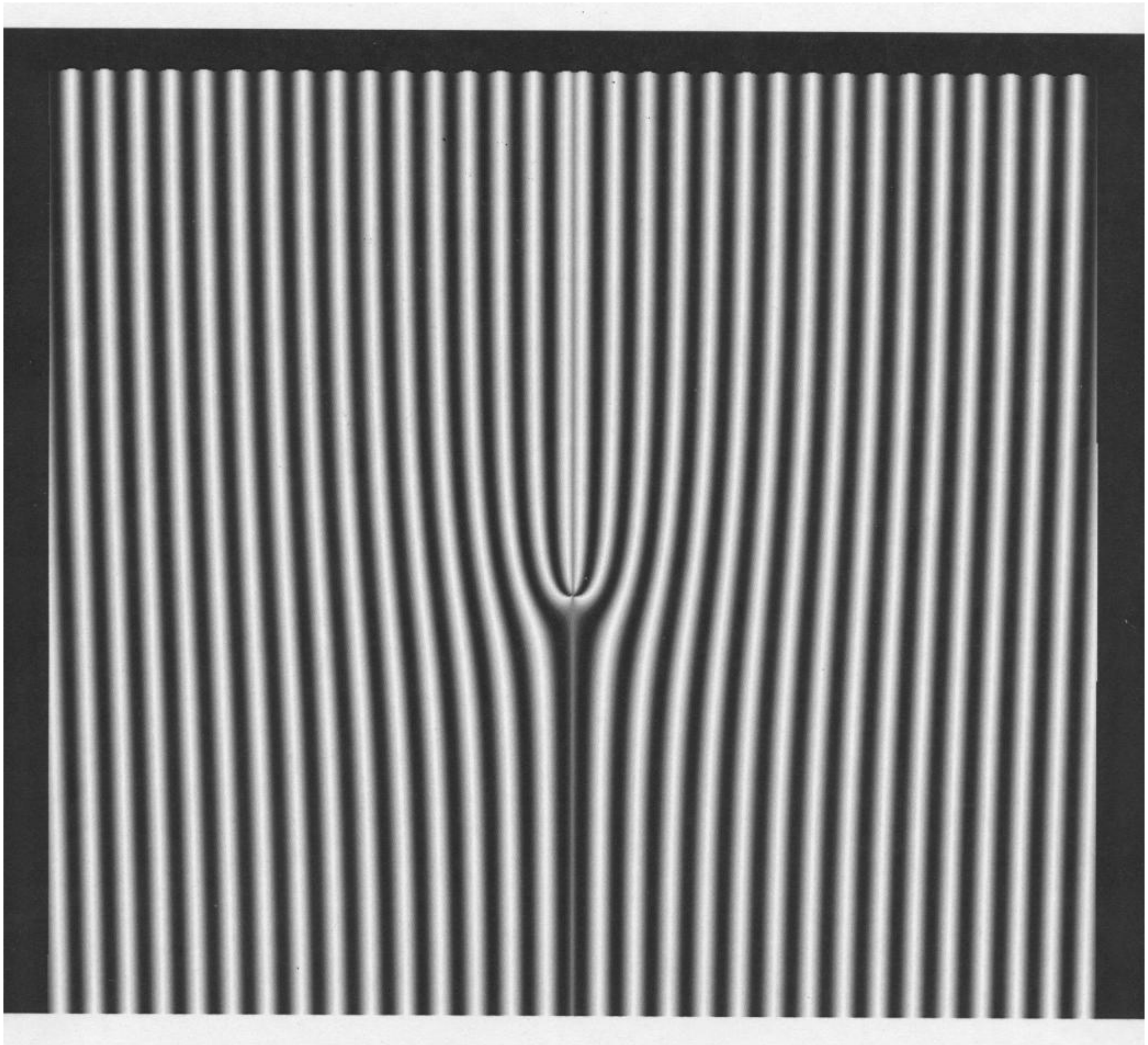


Figure 4 Computer Generated Hologram

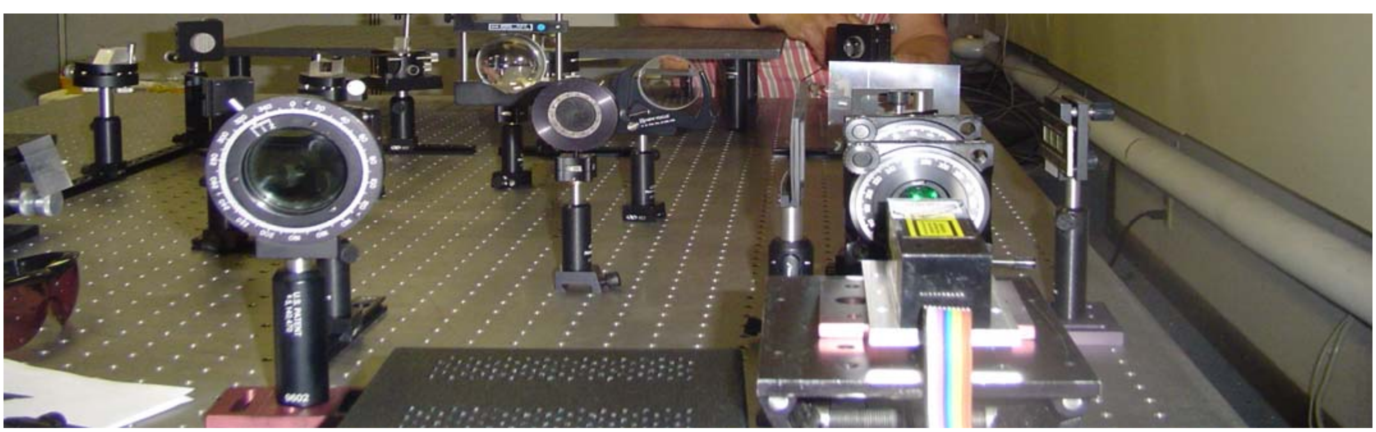


Figure 5 The Free Space OAM Sorter

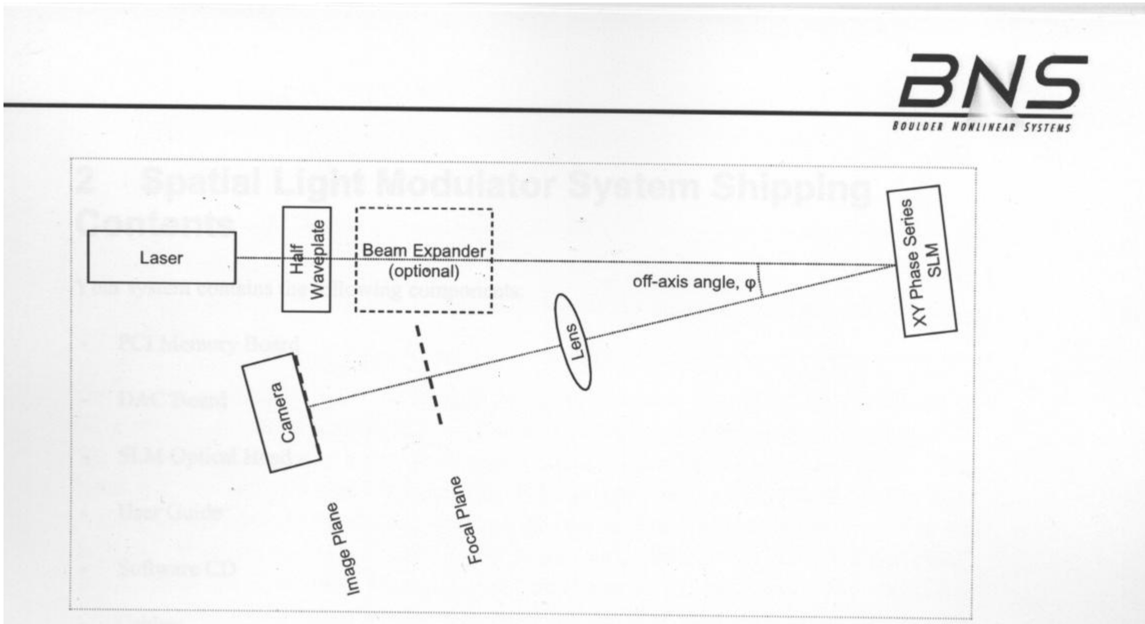
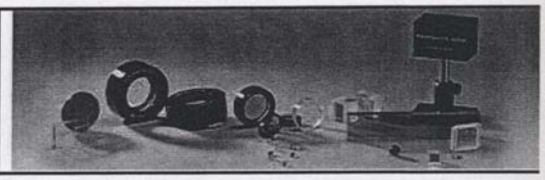


Figure 6 Off-axis optical setup for the XY Phase Series SLM

Information on the Liquid Crystal Retarder

meadowlark optics
polarization solutions



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Resources
About Meadowlark
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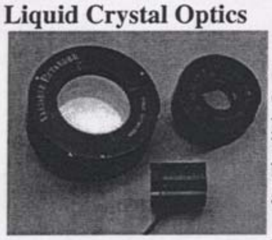
Polarization Control with Liquid Crystal Optics

- Liquid Crystal Variable Retarders
- Liquid Crystal Attenuators, Polarization Rotators, Spatial Light Modulators
- Liquid Crystal Section of the Meadowlark Catalog (1390k, pdf)
- Velocity Ferro-electric Liquid Crystal Shutters

Meadowlark Catalog

Liquid Crystal Optics



Meadowlark Liquid Crystal Variable Optics are solid state, real-time, continuously tunable devices made from nematic liquid crystal polymers. Nematic liquid crystals are birefringent materials whose effective birefringence can be changed by varying an applied voltage.

Meadowlark Optics' liquid crystal optics are constructed using precision polished, optically flat fused silica windows spaced a few microns apart. The cavity is filled with nematic liquid crystal material and sealed. This assembly ensures excellent transmitted wavefront quality and low beam deviation required for many demanding applications.

The long axis of the liquid crystal molecules defines the extraordinary (or slow) index. With no voltage present, the molecules lie parallel to the windows and maximum retardance is obtained. When voltage is applied across the liquid crystal layer, the molecules tip parallel to the applied electric field. As voltage increases, the effective birefringence decreases, causing a reduction in retardance.

Custom retardances can be achieved by using high birefringent materials and/or increased liquid crystal layer thickness. Birefringence of liquid crystal materials decreases at longer wavelengths, requiring proper evaluation and design for optimum performance.

Liquid Crystal Variable Retarders

Meadowlark Optics award-winning Liquid Crystal Variable Retarders provide precise solid-state retardance tunability. These true zero-order devices are precision engineered, offering excellent performance in the visible to near infrared region. When combined with other optical components, our Liquid Crystal Variable Retarders produce electrically controllable attenuation, linear polarization rotation, or phase modulation.

Our liquid crystal retarders are sensitive to temperature and wavelength changes, and can be calibrated to provide high precision tunable retarders, insensitive to temperature or wavelength change.

Liquid crystal retarders offer outstanding performance over large incidence angles. Material type, cavity thickness, and especially operating voltage play a large role in determining the acceptable input angle.

Phase control or modulation is possible for light linearly polarized parallel to the slow axis. Electrical control of the effective extraordinary index allows precision tuning of an optical phase delay in the propagating beam.

Continuous tuning of retarders over a broad wavelength range is required for many applications. This added versatility makes real-time polarization conversion possible with a single Liquid Crystal Variable Retarder and electronic controller. Figure 1 shows a variety of output polarization forms achieved with a single device. Pure phase modulation is accomplished by aligning the optic axis of the liquid crystal retarder parallel to a linearly polarized input beam.

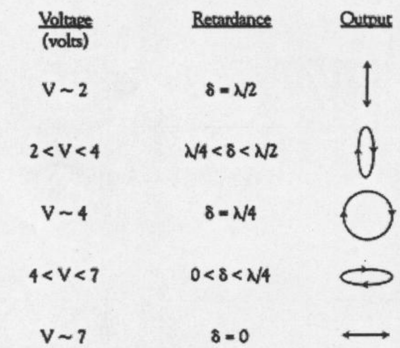


Fig. 1. Output polarization forms from different retardance values of a compensated variable retarder with horizopntal linearly polarized input

Liquid Crystal Attenuators, Polarization Rotators, Spatial Light Modulators

A Liquid Crystal Variable Retarder is the fundamental component used in the following devices and systems.

- variable attenuators
- variable beamsplitters
- spatial light modulators
- non-mechanical shutters
- beam steerers
- polarization rotators
- optical compensators
- polarimeters
- tunable filters

These products all use nematic liquid crystal materials to electrically control polarization. Meadowlark Optics' standard liquid crystal products provide tunable retardation by changing the effective birefringence of the material with applied voltage, thus altering the transmitted light to some elliptical polarization form.

Variable attenuators with no mechanical rotation are configured by placing a Liquid Crystal Variable Retarder between crossed polarizers. Full 180° linear polarization rotation can easily be achieved by combining the Liquid Crystal Variable Retarder with a fixed quarter waveplate. Liquid crystal Spatial Light Modulators (SLM) consist of individually controllable pixels. These devices are used in a variety of intensity and/or phase control applications where spatial variation is required. Refer to the Spatial Light Modulator section for details and specifications on these innovative products.

To learn more about Meadowlark Liquid Crystal Optics and Drive Electronics:

- Click on the link above for the entire Meadowlark Catalog
- Click here for the Liquid Crystal Section of the Meadowlark Catalog.
- Follow the link in the menu above to Meadowlark Application Notes for more information on Nematic LC properties.

Velocity Ferro-electric LC Shutters

Velocity variable shutters and choppers are offered by special order. Please call Meadowlark for more information.

Figure 7 Information on the Liquid Crystal Retarder